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Original Article

Development of forming tool concept validator with variable stiffness blank-holder for high strength steel applications

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A B S T R A C T

This paper presents numerical and experimental results of a prototype tool that includes blank-holder elements of variable stiffness. The application is developed for high-strength steel applications aiming to achieve improvements in the forming operation, namely expand the limits of formability for the tested materials. A numerical model was built including material constitutive models description for the high-strength steel grades used while a forming tool was designed and constructed in order to evaluate the proposed concept. The obtained experimental and numerical results show a positive geometry control and reduction of failure risk. These results are a contribution to the validation of a variable-stiffness blank-holder concept for this particular case study.

1. Introduction

Weight reduction in the automotive has been achieved relying on different materials/technologies. One of the prominent approaches is the use of higher-strength materials with increased deformability at higher-strength levels and improved energy-absorption capabilities for crashworthiness related parts. The objectives of weight-reduction have favoured the use of such HSS and UHSS (Ultra High Strength Steel) grades over the years which posed challenges for manufacturing methods leading, for example, to an increase in hot forming techniques. However, such technology is expensive and energy consuming, therefore there is a need to increase the range of application of high-strength steels with cold forming processes.

Metal forming of parts in advanced high strength steel grades must consider several factors such as thickness reduction, spring-back, forming defects and manufacturing feasibility. One possible approach is to exert influence in the blank-holding force of cold-forming process. Although hydraulic systems can be used, careful tailoring of blank-holder plates in what regards their stiffness is a possible alternative. This implementation is analysed in the current study recurring to a numerical model and experimental tool prototype for a relevant part.

Different strategies can be used regarding the intervention on blank-holder loads: use of elements of variable stiffness via a segmented geometry [1]; multi-point hydraulic actuators [2]; mobile hydraulic plates (shimming) [3]. A method of controlling the support through gap holding was also described in Ref. [4].

Of the described approaches the segmented geometry provides the simplest form of implementation of a variable-stiffness blank holder. Brabie and co-authors [1] studied tools where the forming support was constructed from two concentric rings and having the possibility to be manufactured using different materials. Therefore this implementation allows a reduction of thickness variation in small parts. The authors reported a 35% reduction of variation of thickness and defect reduction of 20% [1]. Another report [5] used a modification in friction conditions of the forming support having, spiral springs introduced in order to reduce the friction and increase stretching of the material to be shaped. Such implementation allowed for quality improvements in the embedding of square geometry cups [5]. One disadvantage of a segmented geometry for the cushion design is the higher level of complexity involved that is also highly dependent of the actual geometry to manufacture and therefore requiring a specific design. One such example of complex design included a double-ring shaped support of conical geometry for the purpose of introducing variable support load in precision-forming of components with axial symmetry [6]. In that study

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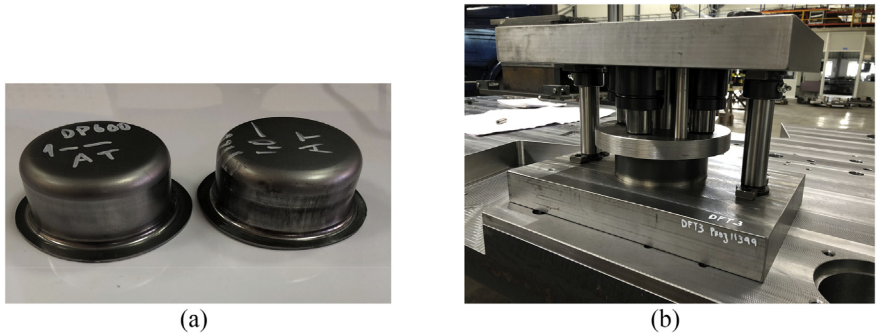


Fig. 1. (a) Final manufactured parts; (b) Prototype validation tool.

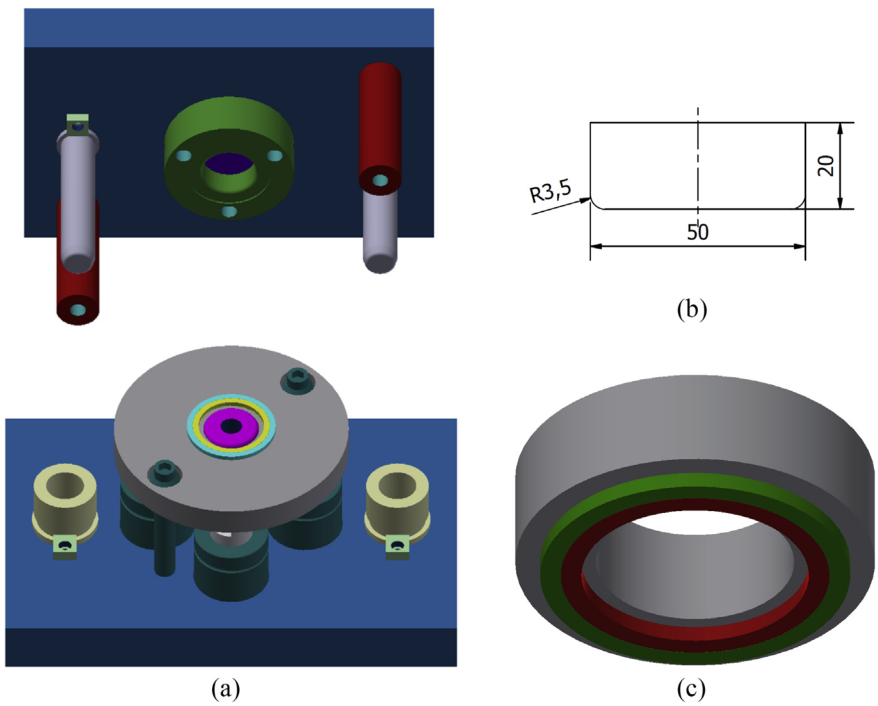


Fig. 2. (a) Validation tool modules; (b) part design; (c) blank-holder and segmented ring design (inner ring in red).

improvements were reported in the quality as well as dimensional accuracy of the components produced [6].

A tool design with the possibility to modify blank holding forces is also considered relevant for manufacturing techniques using multi-thickness sheets obtained by laser welding [7] or plates with varying thickness obtained in the rolling process [8]. Such developments are increasingly used in the automotive industry since they allow the possibility to manufacture optimized components of variable thickness. However, such parts present problems of distortion, differential elastic return and localized fracture that can be mitigated through the control of restriction loads in the blank support [9].

The acquisition of knowledge and increase of manufacturing expertise with high-strength steel grades benefits application in other industries where weight reduction is pursued, such as personal protection devices [10], or general equipment construction. The knowledge transfer from the automotive industry, wherein specific materials characterisation protocols [11,12] and simulation tools [13] are used can benefit improvements in design and weight reduction for other products.

2. Materials and methods

This study presents experimental and numerical findings related to a validation part/tool that is presented in Fig. 1. The validation design consists of a cup drawing part (having 50 mm diameter, total height of 20 mm and punch nose radius of 3.5 mm – Fig. 2b) manufactured in a tool working with a two step process. The choice for a two-step process results from experience of the company in multi-step forming tools where the final shape is

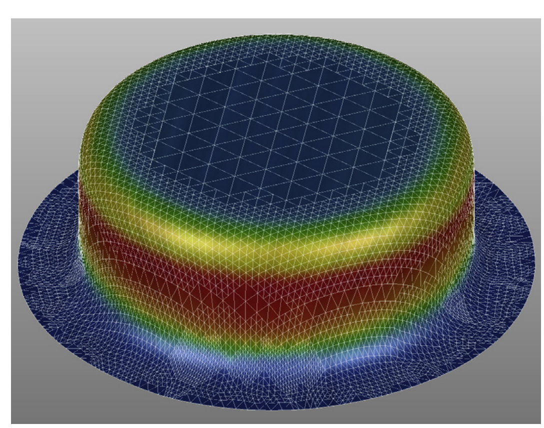


Fig. 3. Finite element model.

Fig. 4. Stress-strain curve, yield surface and FLD curves for DP1000 (Autoform library).

Table 1
Numerical and experimental material/thickness combinations.

Material	Thickness	Blank-holders
DP1000	1.0 mm and 1.5 mm	SS/TT/ST/TS
M1200	1.0 mm	SS/TT/ST/TS

Table 2
Mechanical and physical properties.

	DP1000	M1200	Construction steel	Teflon
Density (kg/m^3)	7840	7840	7850	2160
Young's Modulus (MPa)	2.08×10^5	2.05×10^5	2.00×10^5	540
Poisson coefficient	0.26	0.24	0.30	0.46
Yield stress (MPa)	754.4	1128	250	40

obtained from a series of incremental operations. The core of the innovation analysed is the use of a segmented blank-holder allowing a variation of stiffness and therefore of the clamping condition at the sheet metal surface. The implementation of this approach is based on reference [1], although adapted in size and for a two-step process.

The approach adopted for the validation of the forming concept validation is presented in Fig. 2: a circular blank-holder element of the tool is divided in two parts (rings) thus allowing different materials to be used, which for the present study are conventional construction steel and Teflon. The rational for this choice is to mix-match materials with very different Young's modulus hence stiffness behaviour. According to Fig. 2c a nomenclature is defined as “12” where “1” refers to the material in the inner ring and “2” refers to the material in the outer ring. For example: ST refers to an inner ring in Steel and outer ring in Teflon. Based on the referred nomenclature the following combinations were analysed: full steel (SS), full Teflon (TT) and combination of the two materials. (ST and TS). The rings were manufactured with a 10 mm height and having diameters defined for the inner ring (internal diameter 55 mm and external diameter 65 mm) and outer ring (internal diameter 65 mm and external diameter 75 mm). The blanks used have diameter of 85 mm. The forming tool is prepared for use in two incremental steps of 10 mm displacement allowing for a final depth of 20 mm. A static load of 58.8 kN was imposed in the top plate supporting the blank-holders (Fig. 2c) through four hydraulic cylinders that are visible in Fig. 1b. The punch actuation was performed in an industrial mechanical press (Mecfond S4-800).

For this validation study the parts were manufactured in high strength steel grades of the types: Dual-Phase and fully martensitic. Dual-Phase steels have a ferritic–martensitic microstructure where a soft ferrite matrix contains islands of martensite as the secondary phase (martensite increases the

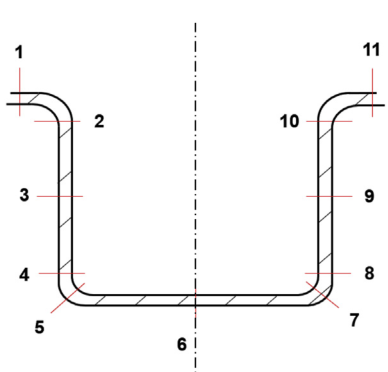
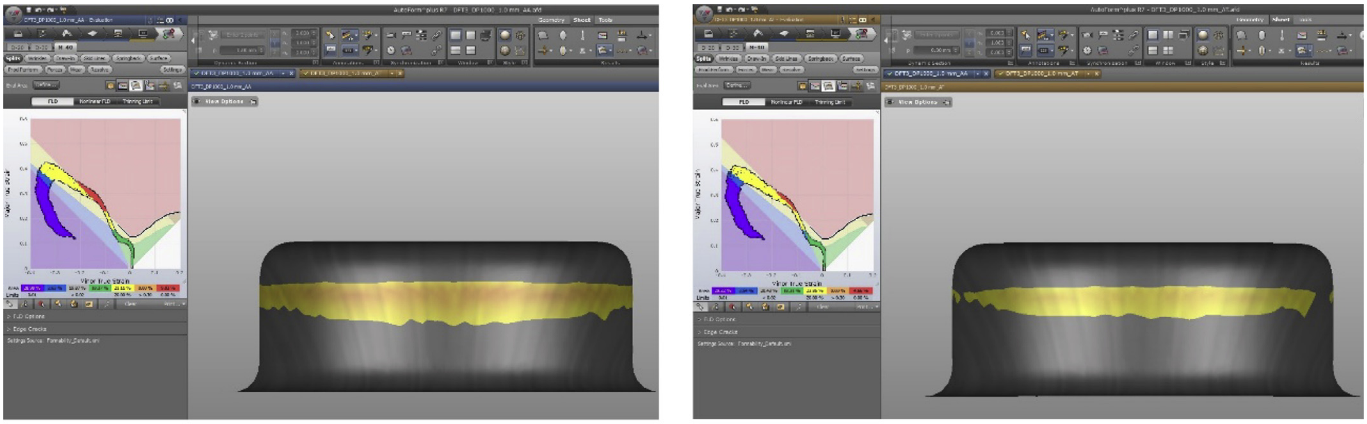


Fig. 5. Reference geometry points for thickness measurement along the meridian contour.

Table 3
Overview of qualitative experimental forming results.

Steel/thickness	Blank-holders	First step	Second step
DP1000 1.0 mm	SS	v	rupture
	ST	v	v
	TS	v	v
	TT	v	wrinkles
DP1000 1.5 mm	SS	rupture	–
	ST	v	v
	TS	v	v
	TT	v	v
M1200 1.0 mm	SS	v	rupture
	ST	v	v
	TS	v	v
	TT	v	wrinkles



(a) (b)

Fig. 6. Failure risk as presented by Autoform software in FLD diagrams: (a) DP1000; 1.0 mm; SS blank-holders; (b) DP1000; 1.0 mm; ST blank-holders.

tensile strength). Such microstructure provides mechanical properties of interest for automotive parts [11]. The steel grades used were supplied by ArcelorMittal: DP1000 in 1.0 mm and 1.5 mm thickness and M1200 in 1.0 mm thickness.

3. Numerical model

A finite element base model was constructed in Autoform software with the following options on mesh definition: automatic meshing with local refinement defined by the highly automated Autoform pre-processor. A representation of the finite element mesh for the part is presented in Fig. 3. The main contact definitions chosen are: *bonded* definition between blank-holders and the top load transmission plate; *frictional* contact between punch and material to be formed as well as material to be formed and blank holders. The friction coefficients were defined as: 0.16 for the steel-steel contacts; 0.04 for the Teflon-steel contacts. The operation was modelled through sequential displacement imposed in the tool punch of 10 mm and 20 mm. A static load of 58.8 kN was imposed in the top plate supporting the blank-holders (Fig. 2c) replicating the experimental conditions of the blank-holder load.

Nonlinear behaviour of the Dual-Phase and Martensitic steel grades was included in the model through the available and extensive Autoform library. This library includes for the DP1000 and M1200 materials the Swift model as hardening curve and the BBC model for the yield surface description. An example of the information available is presented in Fig. 4. A summary of the numerical case studies is presented in Table 1. Relevant mechanical and physical properties of materials are presented in Table 2.

4. Results and discussion

The presented results have focused on failure risk as presented by Autoform post-processing in FLD curves. This is to be compared with experimental results regarding the presence of cracks or other

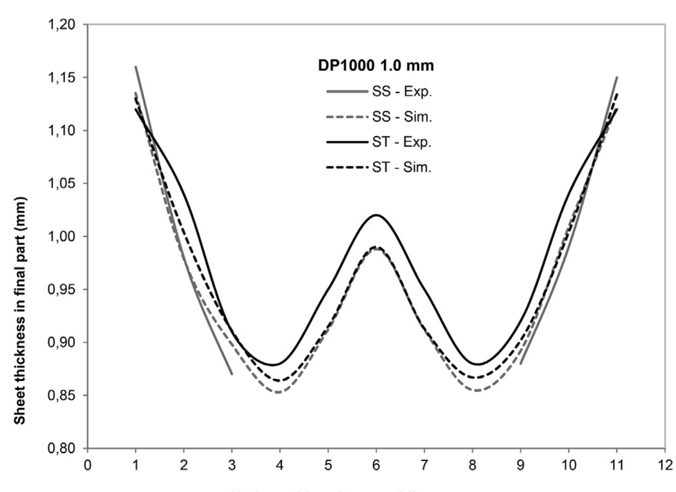
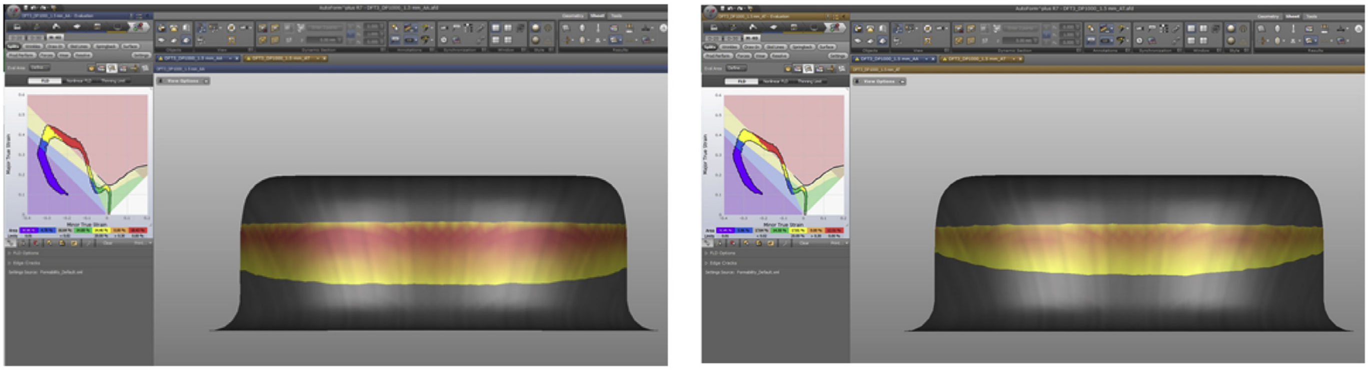


Fig. 8. Experimental and numerical results of thickness reduction (DP1000 1 mm) – incomplete curve indicates fractured part.

(a) (b)

Fig. 7. Manufactured parts. (a) DP1000; 1.0 mm thickness; blank-holders TS and TT; (b) First step and second step (failure) with blank-holders SS.



(a) (b)

Fig. 9. Failure risk as presented by Autoform software in FLD diagrams: (a) DP1000; 1.5 mm; blank-holders SS; (b) DP1000; 1.5 mm; blank-holders ST.

Fig. 10. Manufactured parts: DP1000; 1.5 mm thickness; blank-holders ST and SS (failure in first step).

manufacturing defects, such as wrinkles. Thickness variation along an established profile (Fig. 5) is also analysed while comparing numerical and experimental results. This is also indicative of failure risk as well as to springback/geometry behaviour. Thickness variation was obtained from measurements in a 3D coordinate measuring equipment (Aberlink Axiom Too) placing each part in a fixing jig allowing internal and external access along a meridian contour.

An overview of the experimental results is presented in Table 3 detailing the qualitative outcome of the forming process in each step for the different material/thickness combinations. For a more detailed presentation of results the most representative cases are used, namely the comparison of SS and ST blank-holder combinations.

Figs. 6–8 present selected numerical and experimental results for steel grade DP1000 in 1.0 mm thickness. In Fig. 6 the numerical post-processing of Autoform presents failure risk as a colour graph with correspondence to FLD diagrams. The interpretation of Fig. 6a indicates that a significant number of elements (presented in red colour) have a high failure risk. For comparison, in Fig. 6b a lower failure risk is apparent. Fig. 7 illustrates final parts for this material/thickness combination where geometric defects are visible for the TT blank-holder combination. Values of sheet thickness in the final part are presented in Fig. 8, for the points referenced in Fig. 5. For this particular case it is observed that although numerical and experimental results are not coincident the overall trend can be predicted. For the presented results and improvement in thickness reduction severity is possible with the ST blank-holder combination over the full steel blank-holder, therefore in agreement with the results presented in Fig. 6.

Figs. 9–14 present selected numerical and experimental results for the other analysed steel grades (DP1000 in 1.5 mm thickness and M1200 in 1.0 mm thickness) following the same type of analysis as presented for DP1000 in 1.0 mm thickness.

From the analysis of results several observations can be made and discussed. The tested steel grades and thickness combinations present a challenge for successfully forming the desired part. The main problem is the occurrence of fracture that for some combinations was evident right at the first stage of forming (Table 3, Fig. 10). In Table 3 the qualitative outline of formed parts identifies improvements for the variable stiffness blank-holder approach. However, a balance of blank-holder stiffness is required for achieving the best results since for some full Teflon combinations (TT) the occurrence of wrinkles suggests that sufficient holding load was not present.

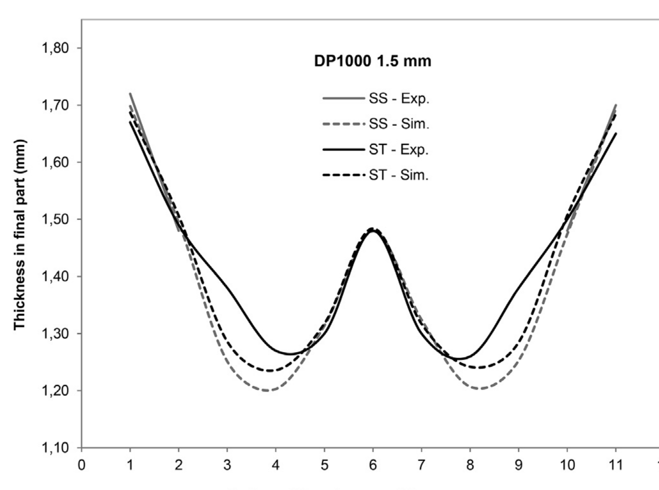


Fig. 11. Experimental and numerical results of thickness reduction (DP1000 1.5 mm).

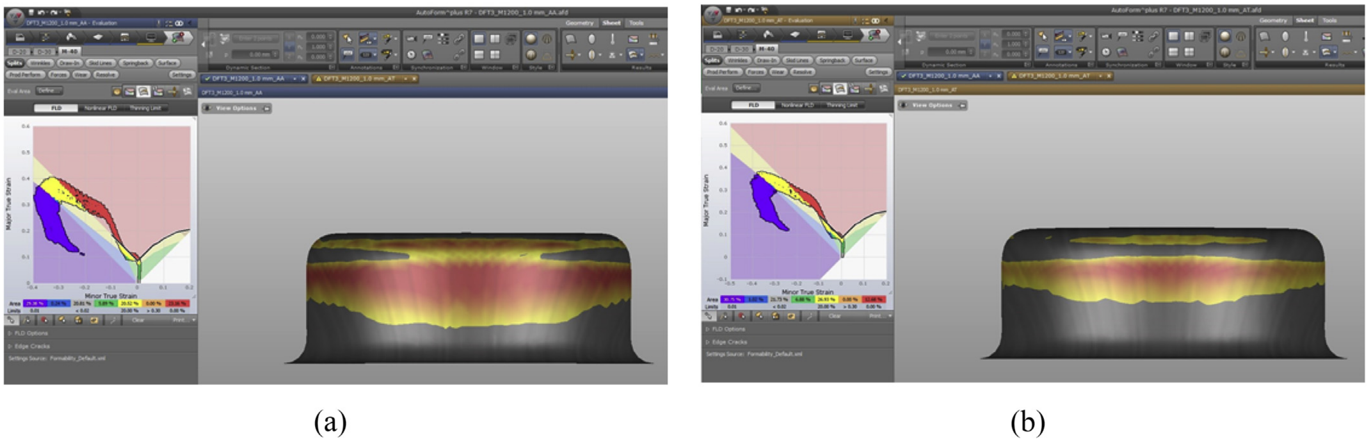


Fig. 12. Failure risk as presented by Autoform software in FLD diagrams: (a) M1200; 1.0 mm; blank-holders SS; (b) M1200; 1.0 mm; blank-holders ST.

Fig. 13. Manufactured parts: M1200; 1.0 mm thickness; blank-holders TS, ST and TT.

The main conclusion to observe for the three analysed materials/thickness is the improvement obtained for a combination of dissimilar stiffness blank-holding rings. For all the analysed cases their introduction either allowed for reduction in the risk of failure or altogether was the decisive factor that made the manufacturing of the part possible. These improvements can be linked to friction coefficient and stiffness. However, the worse performance of the full Teflon blank-holders suggests that stiffness is a dominant factor since in that blank-holder combination the high degree of compliance induced wrinkles in the final part. It is also noted that the combination ST is preferable to TS therefore a higher stiffness is required at the inner ring where the higher bending moment is present. A similar influence of stiffness conditions was reported, although for a bending dominated manufacturing part [14]. In that study a detailed numerical analysis of the blank-holder elements highlighted the influence of the elastic deformation of the Teflon components.

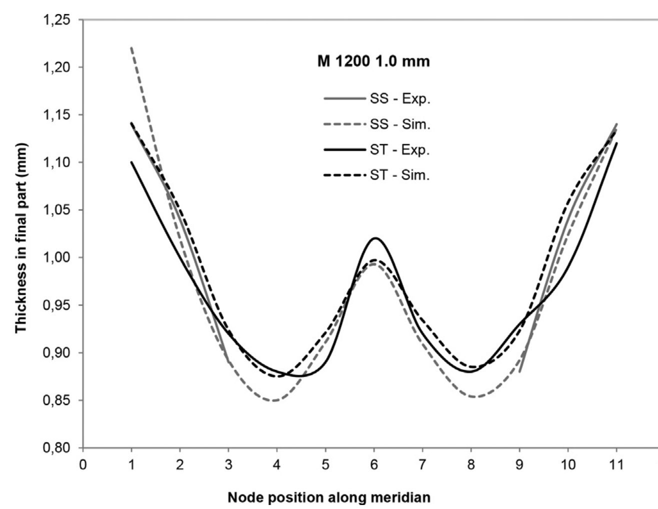


Fig. 14. Experimental and numerical results of thickness reduction (M1200 1.0 mm).

The analysis of Figs. 8, 11 and 14 presents differences between numerical and experimental results. These can be attributed to different factors: mesh detail, contact definitions, differences in material properties (standard material library in Autoform). However, it is noted that both in experimental and numerical results the overall trends are represented, namely in what concerns the improvement obtained with the variable stiffness approach for the blank-holders.

5. Conclusions

This study presented numerical and experimental results for parts manufactured in a validation prototype tool having blank-holder elements of dissimilar stiffness. These elements are rings of different materials that form the blank-holder element. The application is aimed at cold forming of high-strength steel parts with improved quality and reducing localized rupture. In a broader sense this development could allow cold forming of complex parts with less steps in a progressive tool or avoiding the need to use other technologies, such as hot forming.

A numerical model was built including relevant nonlinear material constitutive models for high-strength Dual-Phase and Martensitic steels grades while a development forming tool was designed and constructed in order to evaluate the proposed concept. The obtained experimental and numerical results show a positive control of thickness reduction in a challenging geometry and reduction of local rupture. This behaviour is attributed to the localized compliance of the blank-holder, although such compliance must be carefully judged to avoid wrinkle formation. These results are a contribution to the validation of a variable-stiffness blank-holder concept for this particular case study.

Conflicts of interest

The authors declare that there is no conflicts of interest.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijlmm.2019.04.008.

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